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NOMENCLATURE

c_p	specific heat of water at constant pressure, in J/g C
E_p	pumping power averaged over a total period of a cycle, in watts.
E_s	power supplied to the solar collector, in watts.
M	mass of water circulated through the solar collector during the pumping period, in kg.
q	rate of output heat carried by the flowing water through the solar collector, average over a total period of a cycle, in watts.
Q	output heat carried by the flowing water through the solar collector during a heating and pumping period, in KJ.
Re	Reynolds' number of water flowing through the collector.
t_h	heating period in seconds.
t_p	pumping period in seconds.
t_t	total period of a cycle in seconds, $t_t = t_h + t_p$.
T_i	temperature of the cold water entering the solar collector in °C.

T_m	mean temperature of the water collected from the outlet of the solar collector during the pumping period in °C .
ΔT	temperature differential: temperature difference between the outer surface of the collector outlet pipe and the water storage tank outlet pipe which is connected to the collector inlet via the pump, in °C.
ON:	the temperature differential at which the control device switches on the power to the ~~water~~ pump.
OFF :	the temperature defferential at which the control device switches off the power to the pump.
$\dot{V}$	volume flow rate of water through the collector during the pumping period in cm^3/sec .
$\dot{V}_m$	maximum flow rate of water through the collector at which heat transfer equilibrium condition appears and the thermal efficiency is maximum.
ρ	water density in g/cm^3 .
η	thermal efficiency of the solar collector
ν_m	dynamic viscosity of water at T_m , in cm^2/sec .

CHAPTER 1

INTRODUCTION

Flat solar collectors are commonly used for space heating and domestic water heating. The flat solar collector developed in Concordia University has a daily thermal efficiency in the order of 60% .

The thermal performance of the solar collector was first studied by Nabil Nicolas [1]. In his report issued in November 1976, it was concluded that with the increase of water flow rate, the thermal efficiency of the collector first decreases in the laminar flow region and then increases in the turbulent flow region. But there is no sufficient data to support his latter statement.

In order to have a clear and better understanding of the thermal performance of the solar collector in the turbulent flow region, the present experimental investigation emphasizes on the high water flow range. Six temperature differential controls are used for determination of the thermal efficiency of the collector.

CHAPTER 2

THE FORCED CONVECTIVE HEAT TRANSFER SYSTEM

2.0 General

To investigate, experimentally, the thermal performance of a flat solar collector, a forced convective heat transfer system is set up in the heat transfer laboratory of Concordia University as shown in Figure 1. The components of the system are described briefly as follows.

2.1 Solar Collector

The flat solar collector is 91.5 cm wide and 122 cm high. Forty-two 1.27 cm diameter copper tubes flattened to an oval cross-section and parallel to the height of the collector are connected to two horizontal 2.5 cm diameter headers at the top and bottom of the collector with adequate T-joints. The tubes are painted with black enamel. The solar collector is covered with two sheets of glass which have an air space of 2.54 cm in between. Each glass has a thickness of 3.2 mm and a transmittance of 87% . The collector sits on a wooden frame which is well insulated at the bottom and is inclined at an angle of 43 degree to the horizontal.

2.2 Lamp

A lamp with a peak energy at a wavelengh of 1.1 μm and a power of 1600 watts is chosen to simulate the source of solar energy. The lamp is placed parallel to the surface of the collector and at a distance of 34.5 cm normal to the outer surface of the collector glass cover. The lamp is switched on during the entire experiment.

2.3 Water Storage Tank

Water to be supplied to the solar collector is stored in an insulated tank in which a constant head is maintained. To ensure a uniform water temperature inside the tank, tap-water is supplied continuously through the tank, entering at the bottom and leaving to drain at the top.

2.4 Pump

A pump, the suction of which is connected to the water storage tank, provide water circulation at different flow rates through the collector.

The pump is controlled to operate on a switched ON-OFF basis. The period between ON and OFF position, in which water is pumped through the collector, is called the pumping period t_p . Water is pumped through the collector entering at the bottom and leaving at the top.

2.5 Flow Control Valve

The water flow rate through the collector is controlled by a valve at the outlet of the collector. The water flowing through during a pumping period is collected in a container and weighted accurately. The system is set up to prevent water from flowing when the pump stops.

2.6 Temperature Control Device

The temperature control device controls the ON and OFF operation of the pump. The device is controlled by the temperature differential between the outer surfaces of the collector outlet pipe and the water storage tank outlet pipe which is connected to the water inlet of the collector. The device can be set to achieve a desired value of ΔT. Each setting has two operating points, a "ΔT-ON" which controls the power "ON" of the pump and a "ΔT-OFF" which controls the power "OFF" of the pump.

2.7 Temperature Recorder

A multipoint temperature recorder is used to record continuously the temperatures at four points. These four points are shown in Figure 1 and described as follows:

Point 1 is at the outer surface of the outlet pipe of the water storage tank which is connected to the collector water inlet.

Point 2 is in the water inside the inlet pipe of the solar collector.

Point 3 is at the outer surface of the outlet pipe of the collector.

Point 4 is in the water inside the outlet pipe of the collector.

Four copper-constantan thermocouples are used to connect these points to the temperature recorder. Two control wires connect point 1 and 3 to the temperature control device.

CHAPTER 3

METHOD OF INVESTIGATION

3.1 The Operation of the System

Figure 2 shows the temperatures record of two cycles of the system operation. It starts from the bottom of the figure. When the lamp is on and the pump does not operate, the radiation increases the surface temperature of the collector. Heat is transferred from the collector surface to the water inside the collector tubes. As the temperature at the outer surface of the collector outlet pipe, point 3, is " ΔT-ON " degree higher than that of the storage tank outlet pipe, point 1, the temperature control device instantly switches the power to the pump "ON" and cold water is pumped from the storage tank, displacing hot water inside the collector. Temperatures at point 3 and point 1 then decrease. As the temperature at point 3 is " ΔT-OFF" degree higher than that at point 1, the pump is switch to "OFF". The time interval elapsed between the switching 'ON' and 'OFF' of the power to the pump is the pumping period t_p . When the water stops to flow, the temperature of the water inside the collector tubes starts to increase again until a temperature difference between point 3 and point 1 reaches "ΔT-ON" . The time interval between "ΔT-OFF" to "ΔT-ON" is the heating period t_h . The total period of a cycle t_t is equal to the sum of t_p and t_h .

3.2 Experimental Procedures

The experimental produres are as follows:

1. Supply power to the lamp.
2. Choose a setting for the temperature differential control ΔT.
3. Set the control valve to obtain a certain flow rate.
4. Start the heating period, use a stop watch to measure the time and record t_h .
5. Collect all the water flowing through the solar collector during the pumping period and record t_p .
6. Weigh the collected water and record the mass.
7. Repeat steps 4 to 6 .
8. When the pump stops and the heating period starts, change the control valve setting in order to increase or decrease the flow rate.
9. Repeat steps 4 to 8 until the whole operating range is covered.
10. Choose a new setting for the temperature differential control ΔT.
11. Repeat steps 3 to 11.

Six values of ΔT are used in the investigation.

CHAPTER 4

EXPERIMENTAL RESULTS AND CALCULATIONS

4.1 Experimental Results

The temperature at point 1,2,3,4 are recorded on the temperature chart. On this chart the following data are also indicated, the temperature control difference ΔT, the heating period t_h, the pumping period t_p. The experiments are numbered and the mass flow rate of water at each experiment is measured.

4.2 Calculations

The following parameters are calculated from the experimental results:

a. The Mean Temperature T_m

From the temperature chart, T_4 is shown as a function of t_p during the pumping period.

We define
$$T_M = \frac{1}{t_p}\int_0^{t_p} T_4(t)\cdot dt$$

Since the function cannot be integrated analytically, a numerical intergration method is applied.

Using the trapezoidal rule [2], let
$$I = \int_a^b T_4 \cdot dt$$

We devide the interval $a \leq x \leq b$ into n equal subintervals each of width Δt, where $\Delta t = \frac{b-a}{n}$,

then
$$I = \frac{\Delta t}{2}\left(T_{40} + T_{4n} + 2\sum_{j=1}^{n-1} T_{4j}\right) \quad j = 1,2\ldots,n$$

where
$$T_{40} = T_4(a)\ , \quad T_{4n} = T_4(b)$$

$$T_M = \frac{1}{n}\left(T_{40} + T_{4n} + 2\sum_{j=1}^{n-1} T_{4j}\right)$$

b. The Volume Flow Rate $\dot{V}$

$\dot{V}$ is calculated as $\dfrac{M}{\rho_m t_p} \times 1000$ cm^3/sec. ,

where ρ_m is the density of water at T_m .

c. The Reynolds' Number Re

Since the flat collector consists of 42 copper tubes which are flattened into oval shape, in calculating the Reynolds' number we redefine Re as follow:

$$Re = \frac{4R_h}{A \nu_m}\left(\frac{\dot{V}}{42}\right)$$

The equivalent radius R_h of the tube is the ratio of A/P .
Where, the tube cross sectional area A is 0.995 cm^2 ,
the wetted perimeter of the tube P is 4.348 cm ,
ν_m is the dynamic viscosity of water at T_m .
The value of dynamic viscosity ν as a function of temperature T is found from Figure 3 .

d. The Heat Gained Q

The heat gained during the flowing of water out of the collector per cycle is given by

$$Q = M(T_m - T_i)\, c_p \quad \text{KJ.}$$

T_i is the cold water temperature entering the solar collector.

e. The Rate of Heat Transfer to the flowing water $\dot{q}$

$$\dot{q} = \frac{Q}{t_t} \times 1000 \quad \text{watts}$$

f. Power of the lamp E_s

Assumming 80% of the light energy is transmitted to the solar collector, then $E_s = 1600 \times 80\% = 1280$ watts .

g. Thermal Efficiency η

$$\eta = \frac{\dot{q}}{E_p + E_s} \times 100\%$$

The power of the pump E_p as calculated by Nicolas [1] is small as compare to E_s , the power input of the solar lamp. In the calculation of η, E_p can be neglected.

All the results and calculated parameters are tabulated in TABLES 1 to 6 .

CHAPTER 5

DISCUSSION OF RESULTS

5.1 ΔT and t_h

The heating period t_h is independent of the water flow rate but depends on the temperature differential control ΔT. A larger ΔT requires a longer heating period.

5.2 $\dot{V}_m$

When the flow rate is gradually reduced, it reaches to a flow rate at which equilibrium heat transfer condition occurs. At this condition, the temperature of water at the collector outlet keeps constant and the temperature control device does not switch off the power to the pump. This is the maximum flow rate $\dot{V}_m$. The flow is continuous and the thermal efficiency reaches its maximum. Nicolas has mentioned the occurance of such flow rate in his report but he does not submit any experimental data. It is usually hard to obtain $\dot{V}_m$ when the temperature differential control ΔT is large. For a very small ΔT, $\dot{V}_m$ can be recorded. In experiment #139, the value of $\dot{V}_m$ obtained is 12.9 cm^3/sec. When " ΔT-ON " is 8.0 C and " ΔT-OFF " is 2.8 C . Experimental results indicate that the trend for the values of $\dot{V}_m$ increases with smaller ΔT .

5.3 M

The total mass of water collected during a pumping period is increased for small flow rate and small temperature differential control. When $\dot{V}_m$ occurs the mass flow of water is continuous. Figure 4 shows the mass of water collected per pumping period as a function of volume flow rate at different values of ΔT.

5.4 $\dot{q}$

The rate of heat gained by the water flowing through the solar collector as function of water flow rate at six different values of ΔT is shown in Figure 5. It shows that the values of $\dot{q}$ are higher for smaller ΔT at the same flow rate. Curve A shows $\dot{q}$ vs $\dot{V}$ for the lowest ΔT down to curve F for the highest ΔT. A lower ΔT requires a shorter heating period. Hence, the heat lost to the surrounding is less and a higher value of $\dot{q}$ is expected.

For a fixed value of ΔT, experimental data show that the value of $\dot{q}$ decreases as $\dot{V}$ increases in the flow regions below 15 and above 45 cm^3/sec. But, in between 15 to 45 cm^3/sec, there is an increase in $\dot{q}$ as $\dot{V}$ increases. The slope of the increasing curve at this region is steeper when ΔT is large, and the flow rate range of the region is wider for a small ΔT.

In Figure 6, corresponding results of $\dot{q}$ are plotted as a function of Reynolds' number. In discussion of the results we divide the curves into three regions.

Region (1): This region is below Reynolds' number of 50 and is considered as the laminar region. In the laminar flow region, as the pumping period decreases for a higher flow rate, it leads to the increase in number of heating cycles per unit time as the flow rate increases. The increase in the number of heating cycles causes an increase of heat lost from the surface of the collector to the atmoshere. Thus the rate of heat gained by the flowing water $\dot{q}$ decreases as Reynolds' number increases.

Region (II) : This region consists of the part of curves having positive slopes. The range of Reynolds' number varies for different ΔT , and is between 50 to 105. Within this region the turbulence of water flow increases the rate of heat transfer from the collector to the flowing water. $\dot{q}$ increases as Re increases. The slope of the curve in this region is not as steep as that shown in Figure 5 for large ΔT since Re is a function of viscosity which varies as temperature changes. The value of ν as a function of temperature is shown in Figure 3 .

Region (III) : This region is at a higher flow rate range with Re greater than 105 . The value of $\dot{q}$ no longer increases but drops as Re increases. In this region since the heating period t_h is significantly large comparing to the pumping period t_p, the change in pumping time per cycle leads to a slight increase in the number of heating cycles per unit time as the flow rate increase. The heat lost to the surrounding remains almost constant with the change of flow rate. The decrease in value of $\dot{q}$ with Re is mainly due to the decrease in mass and the mean temperature of water collected at the outlet of the collector during pumping period as the flow rate increases.

5.5 Thermal Efficiency η

Figures 7 and 8 show the values of η as a function of $\dot{V}$ and Re respectively. A maximum efficiency of 65% for the smallest ΔT at a flow rate of 17.9 cm^3/sec is recorded. The value of η varies in the same way as $\dot{q}$ as explained in the last section.

CONCLUSIONS

The flat solar collector under investigation operates at high efficiency when the temperature differential control ΔT is small.

The investigation shows that in the laminar region the thermal efficiency of the solar collector decreases as the Reynolds' number increases. Also there exists a region, with Reynolds' number between 50 and 105, at which thermal efficiency increases with higher Reynolds' number. This is due to the turbulence effect of water flow on the thermal performance of the solar collector. In the much higher flow rate region where Re is greater than 105, thermal efficiency decreases as Reynolds' number increases.

A value of $\dot{V}_m$ (17.9 cm^3/sec) is obtained at a temperature differential control "ΔT-ON : 8.0°C " and " ΔT-OFF : 2.8°C ". Thermal equilibrium occurs and the maximum efficiency at this condition is 65% . The value of $\dot{V}_m$ increases as ΔT decreases.

In order to operate the flat solar collector at high efficiency, it is advisable to set ΔT at a minimum acceptable value depending on the applications. In addition, it is necessary to circulate water continuously through the collector with a flow rate approaching $\dot{V}_m$ to reach a heat transfer equilibrium condition.

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TABLE 1 TEMPERATURE CONTROL $\Delta T \begin{matrix} \text{ON} : 8.0\ ^\circ C \\ \text{OFF} : 2.8\ ^\circ C \end{matrix}$ HEATING PERIOD $t_h = 480$ Sec . (average value)

Exp. #	$\dot{V}$ cm^3/s	M Kg	t_p sec	t_t sec	T_m °C	T_i °C	$(T_m - T_i)$ °C	Q KJ	$\dot{q}$ Watts	$\nu_m \times 10^{-2}$ cm^2/s.	Re	η %
143	65.2	13.04	200	756	23.55	14.44	9.10	497.3	657	0.940	151.7	51.3
123	53.8	11.57	215	684	24.07	14.44	9.63	466.5	682	0.936	125.7	53.3
126	50.9	13.00	265	720	23.55	14.44	9.11	515.0	686	0.940	116.7	53.6
129	46.6	13.60	292	760	23.78	14.44	9.34	531.7	700	0.940	108.6	54.7
131	36.9	14.74	400	936	24.72	14.44	10.28	634.6	667	0.925	86.4	52.1
137	31.6	15.68	495	1008	24.98	15.00	9.98	655.4	650	0.920	85.7	50.9
136	29.6	15.54	524	1030	25.30	15.00	10.30	670.8	651	0.910	69.5	50.9
141	22.2	21.09	948	1386	27.29	15.56	11.73	1032.0	745	0.840	57.9	58.2
139	17.9*	15.88	888	--	26.56	15.56	11.00	--	832.7	0.900	41.7	65.0

* At the flow rate of 17.9 cm^3/sec. , equilibrium of heat transfer occurs and the temperature cannot drop to the pre-setted temperature of the control device to switch off the power to the pump. Temperature at the outer surface of the collector outlet is constant and maximum efficiency occures.

TABLE II TEMPERATURE CONTROL ΔT ON : 15 °C OFF: 5.6 °C HEATING PERIOD $t_h = 850$ sec. (average value)

Exp. #	$\dot{V}$ cm^3/s	M Kg.	t_p sec	t_t sec	T_m °C	T_i °C	$(T_m - T_i)$ °C	Q KJ	$\dot{q}$ Watts	$\nu_m \times 10^{-2}$ $cm^2/s.$	Re	η %
101	21.5	13.38	623	1512	31.11	13.33	18.08	996	711	0.85	55.2	55.5
107	25.8	11.90	461	1328	30.71	13.33	17.38	865	651	0.845	66.2	50.9
114	32.6	11.57	355	1160	28.51	13.06	15.45	748.4	645.2	0.860	82.9	50.4
113	39.8	11.00	276	1134	30.07	13.06	16.85	776	686.7	0.832	104.8	53.6
110	43.35	10.32	238	1044	29.59	13.30	16.29	704	674	0.835	113.6	52.7
116	58.5	10.77	184	972	27.28	13.30	13.98	630.4	648	0.876	146.2	50.6
118	66.8	10.09	151	940	27.07	13.30	13.77	581.7	619	0.876	166.7	48.4

TABLE III TEMPE ATURE CONTROL ΔT ON : 23.3 °C OFF: 11.9 °C HEATING PERIOD $t_h = 1400$ sec. (average value)

Exp. #	$\dot{V}$ cm^3/s	M Kg.	t_p sec	t_t sec	Tm °C	T_i °C	$(T_m - T_i)$ °C	Q KJ	$\dot{q}$ Watts	$\nu_m \times 10^{-2}$ $cm^2/s.$	Re	η %
6	69.7	9.41	135	1395	25.49	3.33	22.16	873	625.8	0.919	166	48.9
3	64.4	9.35	148	1512	27.73	3.89	23.84	951.2	629	0.876	160.7	49.1
12	54.2	9.64	178	1512	28.33	4.44	23.89	964.2	637.7	0.876	135.2	49.8
16	50.9	9.98	196	1680	30.08	4.44	25.64	1071	637.7	0.832	133.7	49.8
14	37.4	10.09	270	1782	31.39	4.44	26.95	1139	639	0.800	102.3	49.9
19	34.8	10.20	293	1746	30.89	4.72	26.17	1117	640	0.800	95.2	50.0
18	30.08	10.32	343	1728	32.9	5.56	27.34	1181	684	0.788	83.4	53.4
23	22.9	10.77	470	2016	34.2	4.44	29.79	1343	666	0.760	65.9	52.0
26	16.6	11.23	675	2232	35.03	5.00	30.03	1412	632.6	0.745	48.8	49.4
21	11.0	13.72	1253	2700	37.83	4.72	33.11	1902	704.4	0.702	34.1	55.0
17	7.3	21.89	3000	4440	41.67	4.44	37.23	3411	768.3	0.658	24.1	60.0

TABLE IV TEMPERATURE CONTROL ΔT ON : 26.7 °C OFF: 14.8 °C HEATING PERIOD $t_h = 1750$ sec (average value)

Exp. \#	$\dot{V}$ cm^3/s	M Kg.	t_p sec	t_t sec	T_m °C	T_i °C	$(T_m - T_i)$ °C	Q KJ	$\dot{q}$ Watts	$\nu_m \times 10^{-2}$ cm^2/s.	Re	η %
62	45.3	10.09	223	2016	34.72	4.44	30.28	1279	6345	0.745	132.9	49.6
63	42.8	9.98	233	2016	34.0	4.44	29.56	1235	612.7	0.75	124.9	47.8
64	36.3	9.98	275	1998	34.87	5.0	29.87	1248	624.7	0.745	106.7	48.8
68	26.7	10.32	387	2016	36.24	6.11	30.13	1302	645.8	0.730	80.0	50.5
67	22.8	10.43	458	2034	37.2	5.83	31.37	1370	673.5	0.701	71.1	52.6
66	21.3	10.43	490	2241	38.5	5.56	32.95	1439	642	0.68	68.5	50.2
65	19.9	10.55	530	2376	37.35	4.44	32.91	1454	612	0.701	62.0	47.8
70	14.1	11.22	793	2430	40.0	6.67	33.33	1565	644	0.65	47.5	50.3
69	8.36	15.31	1830	3510	44.8	6.11	38.72	2482	707	0.614	29.8	55.2
72	48.2	9.86	200	1845	34.05	6.11	27.94	1124	611	0.751	140.5	47.8
74	59.2	9.3	157	1620	32.73	7.22	25.51	993	613	0.788	164.3	47.9
73	65.0	9.75	150	1692	30.33	6.11	24.22	989	584	0.832	170.9	45.7

TABLE V TEMPERATURE CONTROL ΔT ON : 37.8 °C OFF: 23.3 °C HEATING PERIOD , $t_h = 2750$ sec. (average value)

Exp. #	$\dot{V}$ cm³/s	M Kg	t_p sec	t_t sec	T_m °C	T_1 °C	$(T_m - T_1)$ °C	Q KJ	$\dot{q}$ Watts	$\nu_m \times 10^{-2}$ cm²/s	Re	η %
41	66.5	9.64	145	2646	41.2	4.44	36.76	1484	560.8	0.646	225.2	43.8
46	51.4	9.87	192	2808	44.4	5.0	39.4	1628	580	0.617	182.3	45.3
58	42	10.09	240	3168	51.84	6.67	46.2	1900	602	0.551	166.8	47.1
50	35.9	10.09	197	3096	50.56	6.11	44.45	1878	606	0.564	139.3	47.3
59	28	10.09	360	3222	51.97	5.83	46.14	1949	605	0.550	111.4	47.3
51	22.6	10.43	462	3330	54.3	6.11	48.2	2102	631	0.533	92.7	49.3
56	18.8	10.32	547	3250	51.2	6.11	45.1	1949	600	0.556	74.0	46.9
57	11.5	11.34	990	3800	55.2	6.39	48.79	2316	609.5	0.523	48.0	47.6
54	7.7	13.15	1708	4600	61.72	6.67	55.1	3031	659	0.468	36.0	51.5

TABLE VI TEMPERATURE CONTROL ΔT ON : 45.6 °C OFF: 30.0 °C HEATING PERIOD $t_h = 3300$ sec (average value)

Exp. #	$\dot{V}$ cm^3/s	M Kg.	t_p sec	t_t sec	T_m °C	T_i °C	$(T_m - T_i)$ °C	Q KJ	$\dot{q}$ Watts	$\nu_m \times 10^{-2}$ cm^2/sec	Re	η_c %
91	64	8.39	131	3366	50.9	5.83	45.07	1581	469.8	0.56	250	36.7
90	48.1	8.62	179	3510	54	5.83	48.2	1738	495.3	0.53	198.5	38.7
89	42	8.28	197	3246	54.93	5.56	49.37	1711	527.3	0.52	175.7	41.2
82	34.3	8.62	251	3573	58.89	5.56	53.33	1925	538.7	0.48	156.3	42.1
88	31.5	8.5	270	3438	58.1	5.56	52.5	1868	543.4	0.489	141	42.5
86	23.8	8.16	343	3294	57.4	4.44	52.9	1808	549	0.5	104.1	42.9
85	20.3	8.71	460	3276	59.1	6.11	53.0	1932	570	0.48	95.2	44.5
83	16.7	8.85	531	3942	59.53	5.0	54.53	2020	512	0.478	76.2	40.0
93	7.7	9.75	1270	3906	65.56	5.83	59.73	2438	624	0.45	37.4	48.8
84	5.5	11.0	1992	4620	71.58	5.56	66.02	3040	658	0.45	26.9	51.4
87	19.2	9.07	471	3870	60.26	5.28	54.98	2088	540	0.478	88.1	42.1

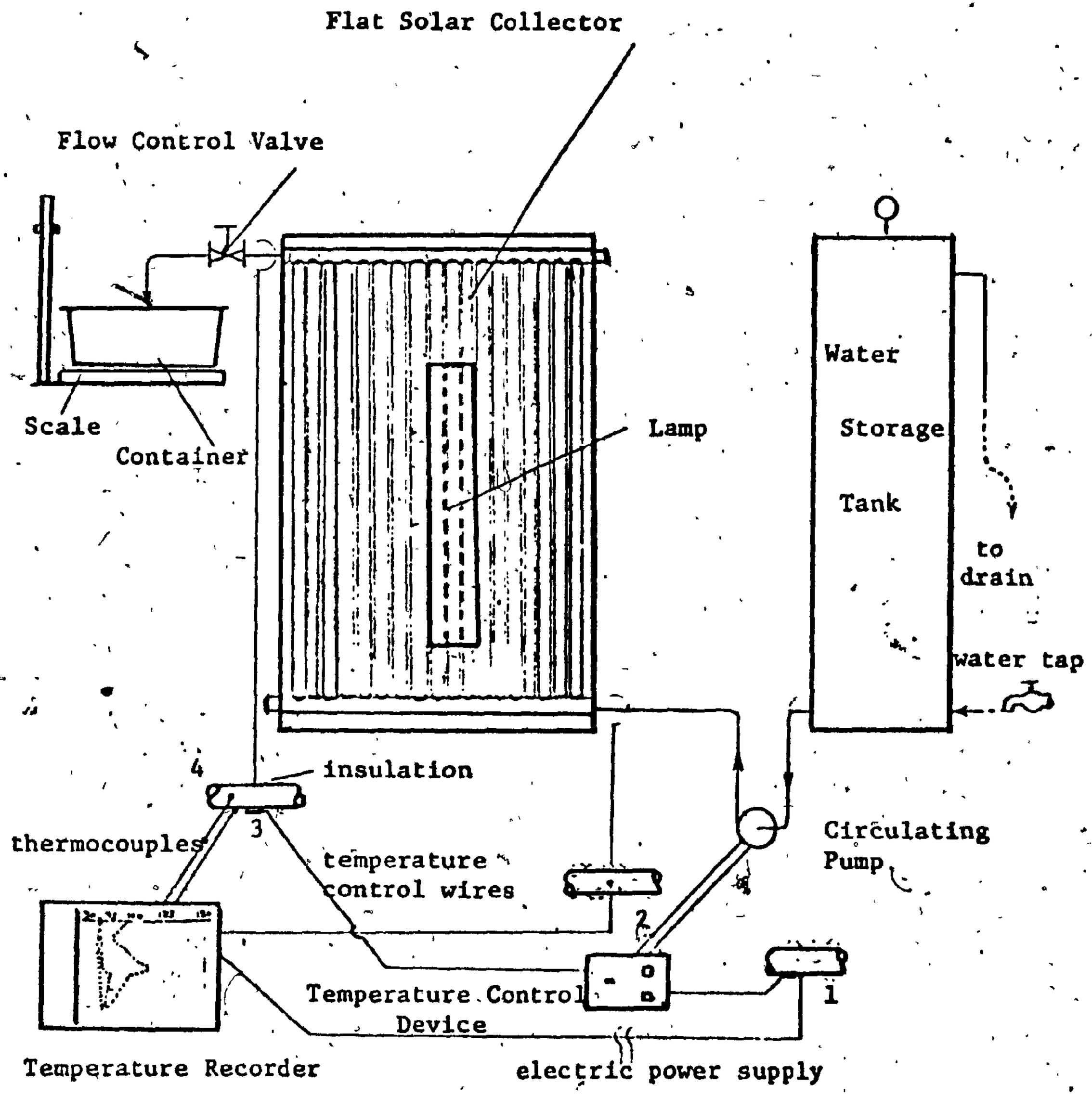

Fig. 1 Schematic diagram of experiment set-up showing solar collector, circulating pump , controls and storage tank.

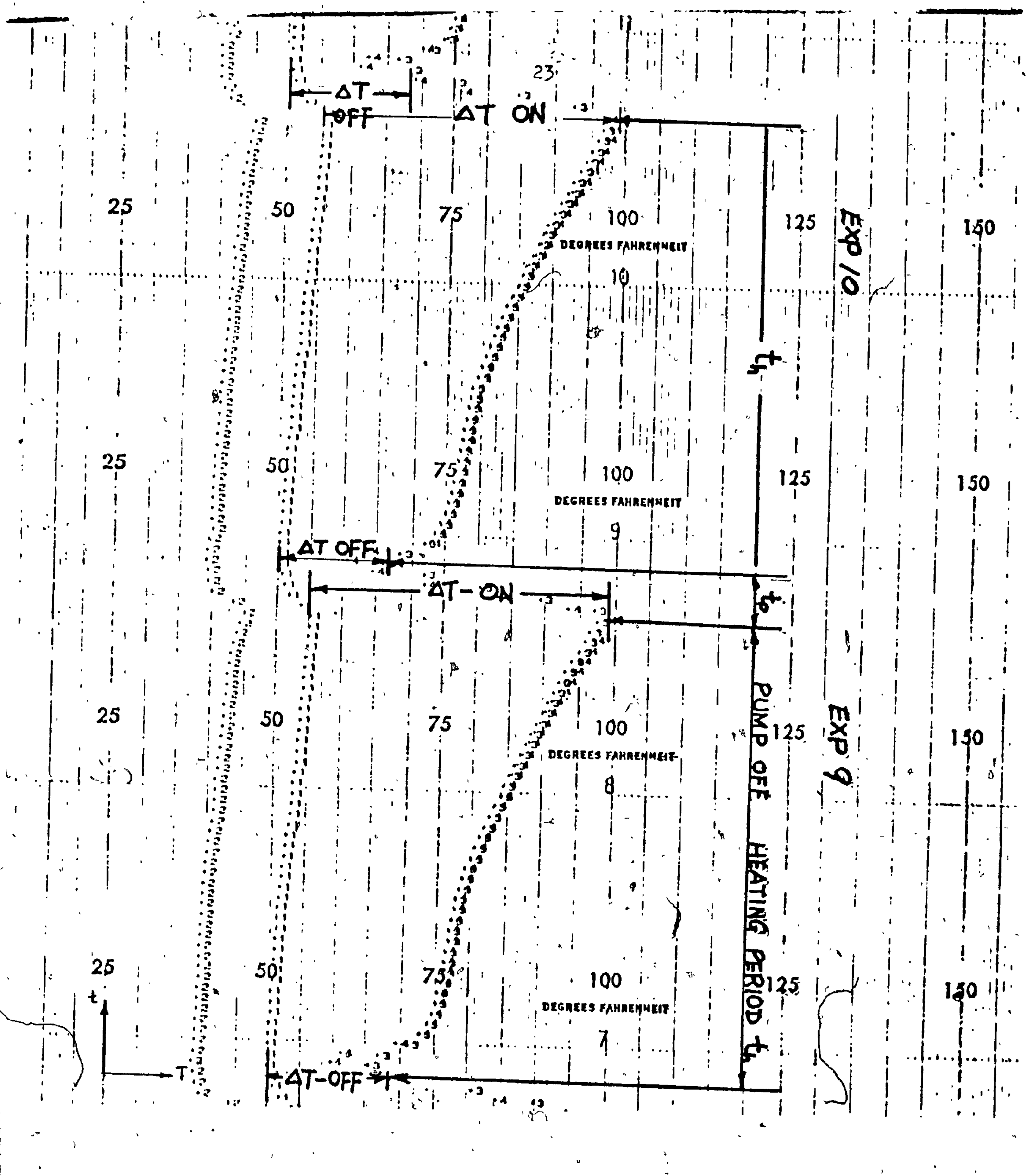

Figure 2 TEMPERATURE RECORDS OF TWO CYCLES

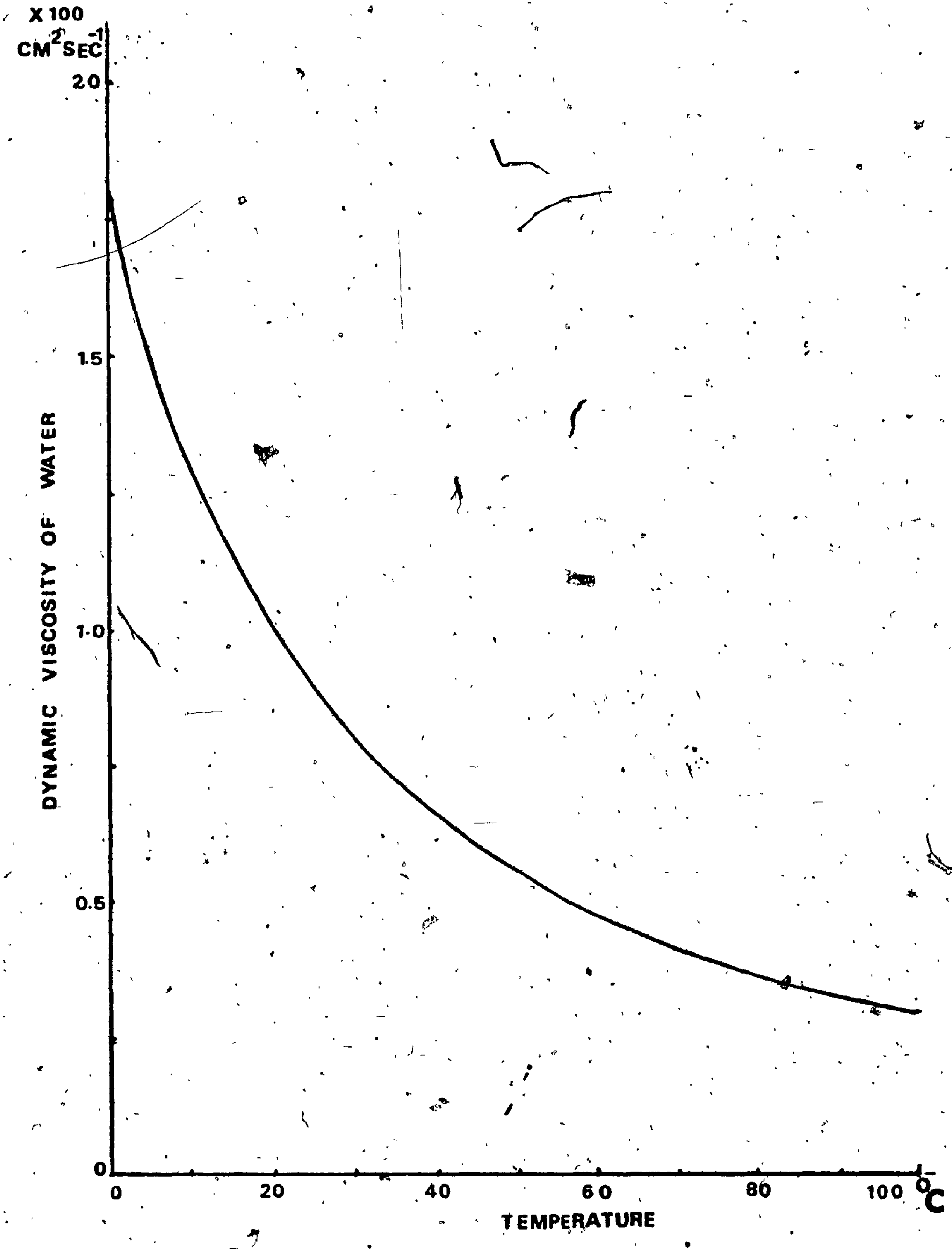

FIG. 3 DYNAMIC VISCOSITY OF WATER VARIES WITH TEMPERATURE [3]

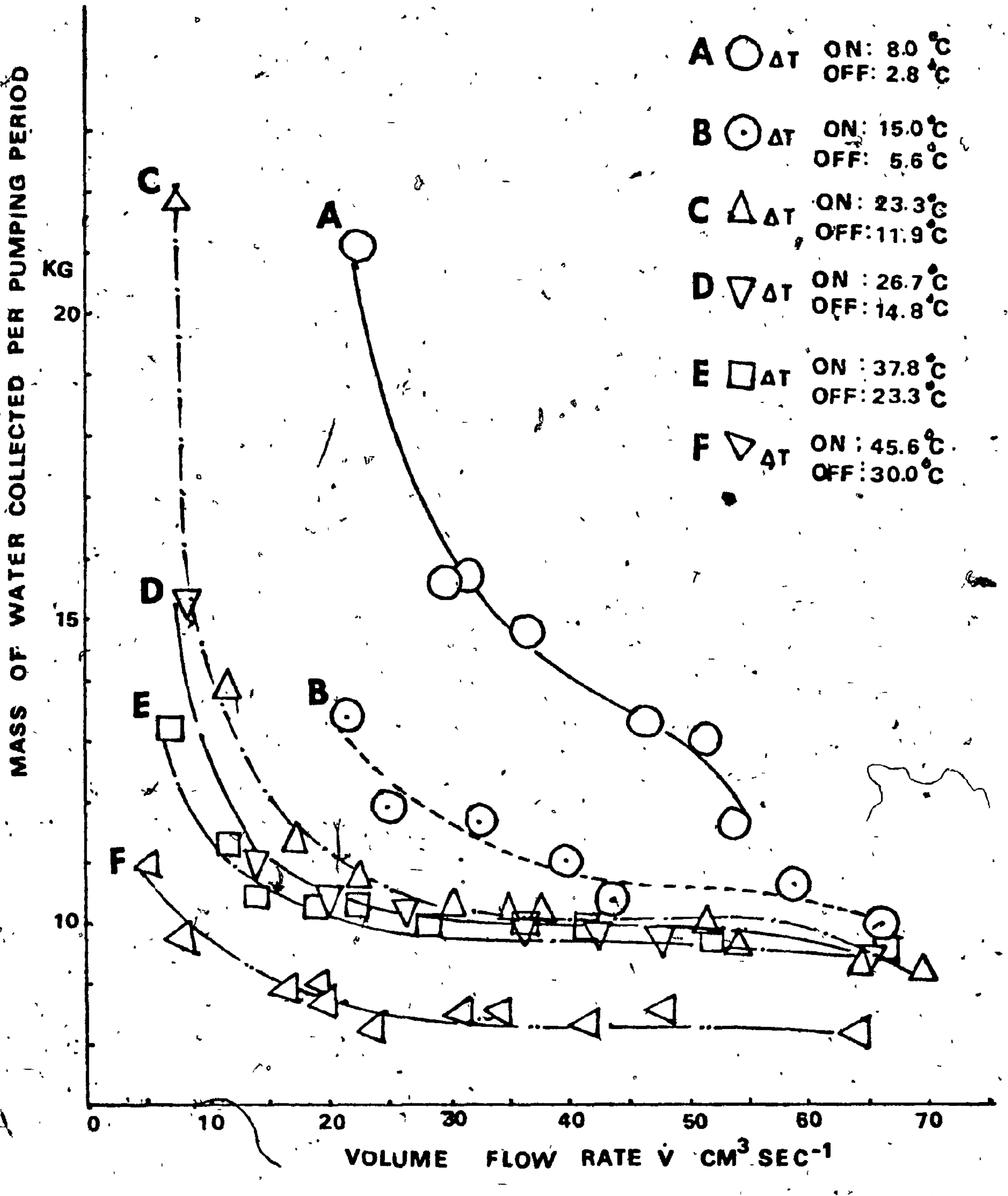

FIG. 4 MASS OF WATER COLLECTED PER PUMPING PERIOD AS A FUNCTION OF $\dot{V}$ AT DIFFERENT VALUES OF ΔT

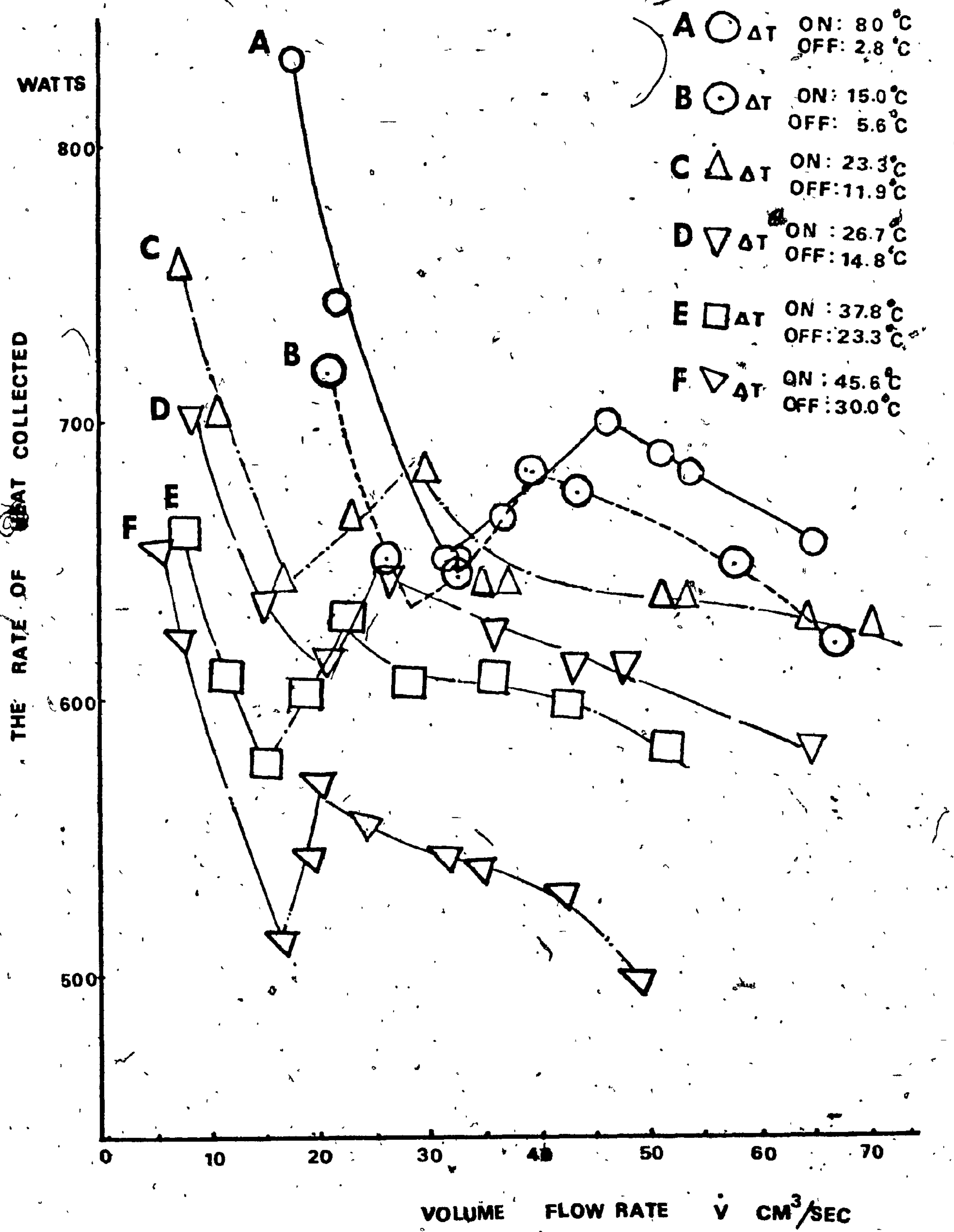

FIG 5 THE RATE OF HEAT COLLECTED AS A FUNCTION OF VOLUME FLOW RATE AT DIFFERENT VALUES OF ΔT

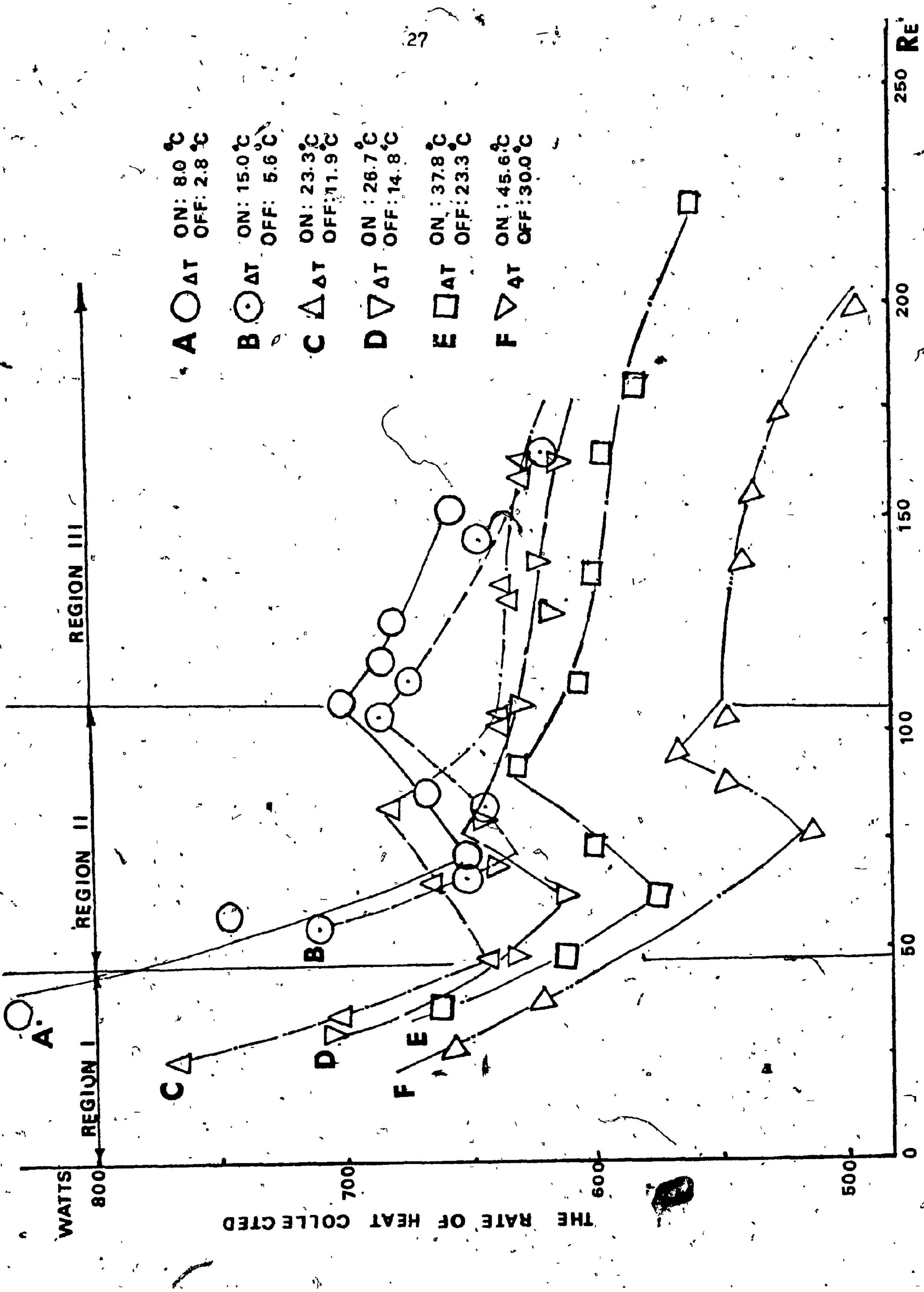

FIG. 6 THE RATE OF HEAT COLLECTED AS A FUNCTION OF REYNOLDS' NUMBER

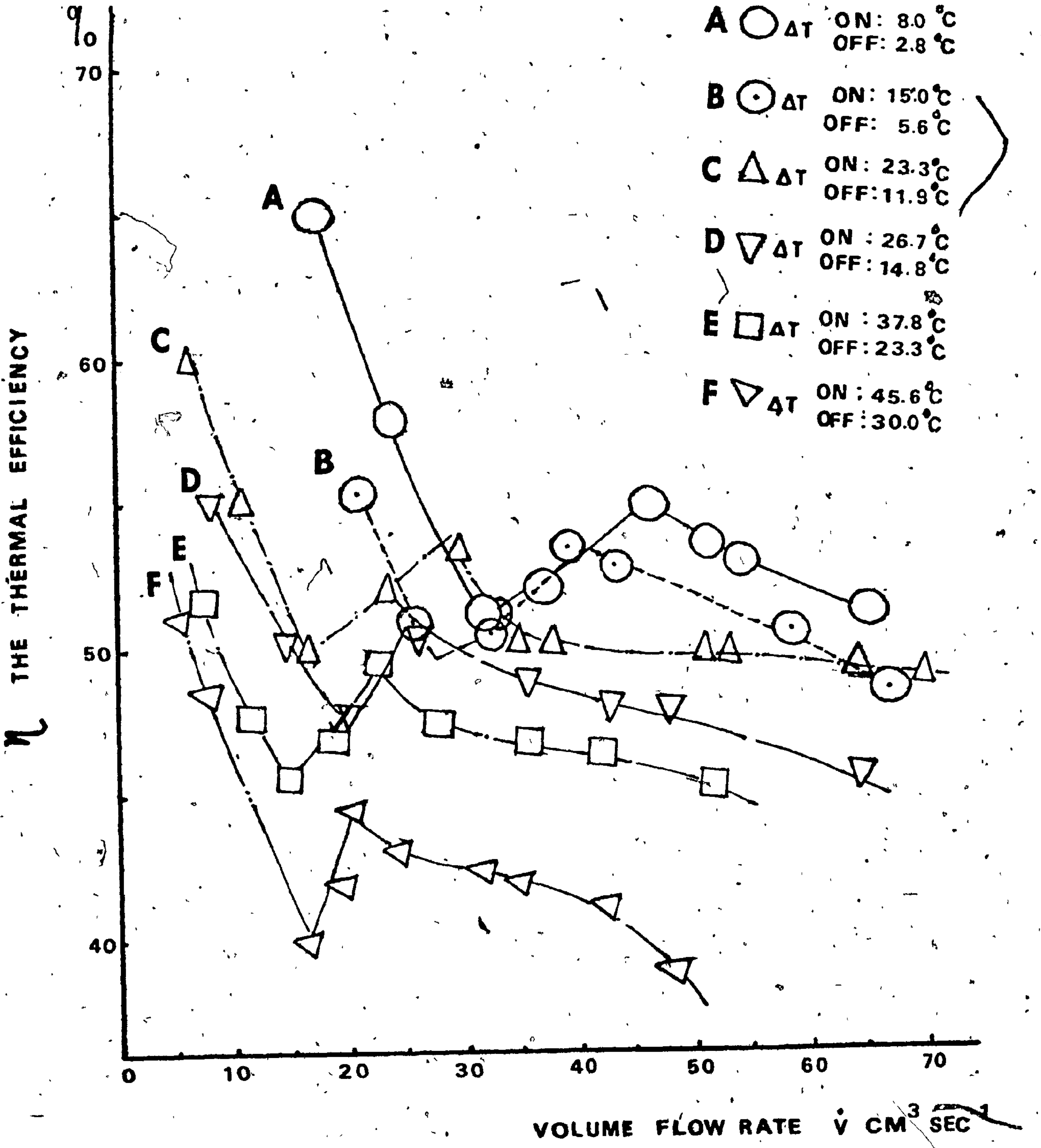

FIG 7 THE THERMAL EFFICIENCY AS A FUNCTION OF VOLUME FLOW RATE AT DIFFERENT VALUES OF ΔT